Flotation stabilization and optimization

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Synopsis

The control of flotation plants is by no means trivial. Flotation is one of the most interactive minerals' processing operations. The interactive nature of flotation circuits results in oscillations of levels and hence of grades and recoveries. Also, poor level setpoint tracking and disturbances have negative influences on grades and recoveries. The result is an unstable plant with limited scope for optimization. An advanced controller, FloatStar™, has been developed to provide tight control and to reduce the amount of disturbances in flotation levels. It has been shown on a number of plants that the system results in faster and better setpoint tracking, better regulatory control and faster settling times after start-ups and disturbances.

The successful stabilization provided by FloatStar has made it easier to investigate the area of optimization on flotation circuits. Mintek has identified the need for a more meaningful set of setpoints or aeration rates to use as a basis for control than levels and have advocated flow control by looking after residence times. When the feed conditions change, the ideal solution would be an algorithm or strategy that finds the new optimum conditions rather than just having an unguided hunt from the previous point. A multivariable flow-optimizing algorithm, a new module in FloatStar, has been developed to calculate optimum level setpoints and/or aeration rates that will aim to optimize the residence times, mass pulls and circulating loads within a flotation circuit.

Keywords: flotation, regulatory, FloatStar, start-up, disturbance, residence times, circulating loads

Introduction

It is possible to obtain good performance from a flotation plant but it has proved difficult to maintain such performance. Recovery rates on a flotation plant can be around 90% and often lower, making flotation one of the least efficient processes in the concentration path. Hence, over the last few decades much research and development has gone into the stabilization and optimization of flotation circuits.

Flotation is a process with many inputs and complex interactions. The modelling of flotation is reviewed by Mathe *et al.*[1] Some current modelling techniques are explained by Manlapig and Franzidis[2], who account for the effects of 'true' flotation, entrainment and froth recovery. Edwards and Flintoff[3] were of the opinion that mathematical modelling and simulation of flotation systems have not evolved to the same extent as comminution.

Technology for the control of flotation circuits has evolved somewhat independently from that of its modelling. McKee[4] describes three 'approaches' required for flotation control: stabilizing, setpoint and optimizing. McKee[5] explains that simple proportional-integral controllers do not provide acceptable responses. Ding and Gustafsson[6] describe the application of a multivariable control strategy for intended application on an industrial flotation plant. They used a linearized model and a linear quadratic gaussian controller. Their results of simulated control are good.

Van Deventer *et al.*[7] suggest that neural networks have provided good scope for the analyses of froth characteristics as functions of their dynamically measured images. Brown *et al.*[8] describe advances in the use of froth imaging technology in process control, on an industrial plant, with improvements in metallurgical importance. It seems that imaging technology is capable of leading to successes in control, but it does also need a lot of work to relate the extra variables it introduces to underlying variables of importance, such as relative flotation rates, entrainment and optimum flow distributions.

Mintek has been very active in the industrial implementation of advanced flotation control for over a decade. Stabilizing level control by its control system FloatStar™ (Schubert *et al.*[9]) has been applied to about thirty flotation circuits, some applications of which are described by Henning *et al.*[10], Singh and Schubert[11], and Muller *et al.*[12]. This paper includes Mintek's recent industrial application of optimizing control, which is being

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implemented successfully at a level above the advanced stabilization.

Mintek's research into flotation control began in the late 1980s when Mintek looked into the optimization of flotation circuits, particularly grade and recovery. These tests involved xanthate addition and its effect on grade and recovery. The results from this test work were not adequate for use in the development of a reasonable model between xanthate addition and recovery or grade. A closer look at the froth-depth data during this period indicated that the froth levels in the flotation cells were oscillating. Hence it was concluded that it was not feasible to measure and model the effect of xanthate on grade or recovery while there are oscillations in level. The movements of the level were causing the grade and recovery to oscillate. Hence the initial focus was placed on level control rather than on the optimization of a circuit that was not stabilized.

Process control and optimization have a direct influence on the efficiency of flotation plants. An inefficient operation can cause an incorrect balance between grade and recoveries and can also lead to adverse shifts in the grade-recovery relationship. Flotation loses the largest proportion of valuable material when compared to other metallurgical processes. These losses can be reduced by improved operation of the flotation process.

Flotation stabilization

Improved flotation operation can be achieved by improved control in terms of stabilization, regulation and optimization of the plant. Through stable operation, the performance of the plant is observed without being obscured by the effects of disturbances and fluctuations. This allows for the optimum conditions to be easily identified. As a result of adequate regulation, the operation is maintained at chosen setpoints, with proper neutralization of the disturbances. Only once proper stabilization and regulation are achieved can the application of an optimizing strategy be applied.

The control of flotation plants can be achieved by controlling aeration rate, reagent addition or froth depth. However, these control actions are effective over different time scales. Reagent addition is slower in its effect as some conditioning time is required. Also since reagents are typically introduced at the head of the circuit and at intermediate points within the banks, it requires time before they start having an effect on flotation performance. Reagent addition, due to its long response time, will therefore be a more effective control action for an optimizing strategy.

Aeration rates and froth depths have a quick and immediate effect on the performance of flotation. They are able to react within a few seconds and make adjustments quickly to counter any deviations or disturbances caused by flow variations. This makes aeration rate and froth depths more suitable to a stabilization control strategy. However, on many plants, aeration rates are not available for automatic control because many conventional cells are self aspirating and airflow can only be manipulated by manual adjustment of the valves. This then leaves froth depth, or its equivalent pulp level, as the most generally used variable for stabilization of short-term disturbances on flotation plants. Obviously other requirements for stabilizing control would be level measurements and automatic control valves.

Levels in flotation cells are conventionally controlled by PI (proportional and integral) control loops. PI control will work well when the cell being controlled is isolated. However, flotation cells are connected in a network and the tailings stream from one cell is likely to be fed to another cell. Similarly, the concentrate flows will generally be fed into banks higher up in the circuit. This results in strong interactions between levels in a flotation circuit. Thus if a change in control action is made at any point in the circuit, this would result in the disturbances being propagated to both upstream and downstream units.

To counter this problem, Mintek has developed and implemented a level controller in FloatStar (Schubert *et al.*[9]) The controller monitors all the levels in the circuit and acts on all the control valves, taking the interactions of levels into account. The advantage is that the control valves on banks further downstream in the circuit can be opened as soon as the disturbances enter the respective banks.

Flotation flow optimizer

Besides its original function of level stabilization, the FloatStar now has additional modules that operate above the stabilization level. Flow optimization is addressed by such a module, which exploits the high quality of the underlying stabilization and provides for the control of flows as well as levels.

The first task in optimizing the process is to decide exactly what targets need to be set. The overall objective is to maximize economic returns, but it can take some thought to formulate how this is best achieved. Incorrectly set targets can be misleading. For example, two commonly used plant objectives are

- to maintain the concentrate grade at a pre-defined level, and
- to maximize the recovery.

If an unsupervised optimization algorithm were set loose with these objectives, it would reduce the throughput if it could, as this will lead to higher recoveries. The detailed objectives will vary from process to process and will depend on metal prices, transportation costs, refining costs and contractual stipulations.

There are many variables to look at when trying to optimize a flotation circuit. These include mass pull, reagent concentrations, air flow rates and level setpoints. With enough process measurements and control elements, a circuit can easily be optimized because there are many degrees of freedom.

Most flotation circuits, however, have limited instrumentation, with only level, valve actuators and occasionally aeration rates for each bank. This leaves basic level control as the only real control in place. With this limitation, flotation operators attempt flotation optimization by changing level setpoints and sometimes aeration rate setpoints to increase or decrease concentrate mass flow rates. However, is the choice of these setpoints correct? If the choice of these setpoints causes the mass balance and the flows to be properly controlled at optimum values then the answer is yes. However, so many combinations of setpoints can be seemingly acceptable, but give inferior overall performance, so more often than not the answer is no.

Once good stabilization control has been achieved, optimization control can be attempted. A step towards optimizing a flotation circuit is to choose the correct level setpoints and/or aeration rates. This can be done in two ways: the first is to change these variables such that the optimum grade and recovery can be obtained. The other, identified by Mintek, is controlling the residence times and circulating flows in the circuit. This is another multivariable, interactive problem. In this case, there are usually more manipulated variables available than controlled variables since level setpoints, aerations rates or frother addition can be manipulated to affect concentrate velocity. The system is therefore over specified, but this can be used very effectively in a multivariable controller to increase the ranges of control. The controller developed by Mintek to accomplish this is now implemented as an optimizing module of FloatStar. This controller ensures that the maximum controllable range and quickest responses are obtained by using all the available manipulated variables to control the circulating flows. Since this control is one level higher (optimization level), the control is slower than stabilization control.

With residence times and mass pulls optimized throughout the circuit, there should be a significant improvement in the performance of the flotation circuit. Also with the mass balance and flows properly controlled, the control of reagents will be able to fit in quite easily to achieve final concentrate grades.

Control implementation platform

The FloatStar is implemented on Mintek's PlantStar software platform. This platform provides for generic functions, such as fuzzy logic, neural networks, rules, and common process-control modules. It also includes process-specific modules, such as the FloatStar, that have been developed to improve on generic methods, to give solutions that include extra know-how on specific processes. The PlantStar provides for the configuration and autotuning of control strategies by 'drag and drop' features and by 'wizards'.

In the application described in this paper, the PlantStar was connected to the plant via a DCS, by the use of OPC. Flotation circuits are fast responding, with the fastest important time constants being in the order of a few seconds. A sampling period of one second was therefore used. Data was stored at one-second intervals. Control actions were calculated and transmitted to the DCS at intervals of one second.

Stabilizing control—industrial application

The application of FloatStar stabilizing control and the benefits derived from it will be illustrated by means of a case study. The section of the flotation circuit chosen for the case study is the cleaner section. The cleaner circuit consists of a recleaner, two cleaners, three cleaner scavengers and two coarse cleaners. All the banks from the cleaners to the cleaner scavengers are in series. That is, the tails of the upstream banks form the feed to the downstream bank. This part of the circuit is very interactive due to the connectivity of the tailings stream. The two coarse cleaners are connected in series on their own, i.e. the tails of coarse cleaner 1 feeds coarse cleaner 2.

The case study compared the performances of control with PID and FloatStar controllers. The PID control was tuned as well as possible. There were no PID settings that gave good control. Derivative action was not practicable because of high measurement noise levels. When the PID controllers were tuned aggressively, they amplified disturbances unacceptably, as the control actions of some loops became disturbances to downstream loops, without compensation for interactions. When the PID loops were detuned, disturbances in flows caused disturbances in levels that tended to be slow and also oscillatory, through the effects of recycled streams.

Statistical level analysis

The data in Table I have been derived from two weeks of performance testing. The control of the flotation circuit was alternated between PID and FloatStar control. The plant was under PID control during the day shift and FloatStar was in control during the night shift. This data was analysed for the standard deviation of the error (difference between level setpoint and measured level) after performing data validation on the data. The statistical analysis of the levels for all the data analysed is given in Table I. The focus is the standard deviation of the error (deviation of level from setpoint) and % improvement. The closer the standard deviation of the error is to zero, the closer the level is to setpoint.

Table I shows a statistical summary of the data analysed for the cleaner circuit. The standard deviation of the error (setpoint—level) for all the levels is smaller with FloatStar control. This is clearly evident from Table I. The percent improvement column confirms the improvement in level control, with the improvement varying between 12.5% and 63%. The data in Table I show that the improvement in level control when FloatStar is in control is significant. Note the % improvement (all over 20% except for the re-cleaner). This is because of the connection of levels via tailings streams and recycling of concentrate streams in the cleaner circuit. Consider a disturbance to the cleaner circuit from the cleaner scavenger tails sump, which feeds cleaner 1 and 2. With conventional PID control this disturbance gets passed to cleaner scavenger 5 and 6 and back through the entire cleaning circuit via the recycle streams. Hence levels will tend to oscillate frequently in the cleaner circuit with PID control

Table I

Statistical summary of cleaner circuit level data

	Control	Mean Level	Level standard deviation	Error standard deviation	% Improvement
Cleaner 1 & 2	PID	43.2	10.7	2.1	**24.4**
	FloatStar	53.5	10.8	1.6	
Cleaner 3 & 4	PID	48.0	10.7	2.6	**51.7**
	FloatStar	54.8	8.6	1.2	
Cleaner scavenger 1 & 2	PID	61.2	7.9	2.8	**23.9**
	FloatStar	61.9	7.1	2.1	
Cleaner scavenger 3 & 4	PID	67.8	7.3	3.3	**50.4**
	FloatStar	69.3	6.5	1.6	
Cleaner scavenger 5 & 6	PID	62.2	4.8	2.8	**36.2**
	FloatStar	60.6	3.3	1.8	
Re-cleaner	PID	49.0	11.6	1.0	**12.5**
	FloatStar	51.5	11.9	0.9	
Coarse cleaner 1	PID	40.8	11.3	2.9	**21.6**
	FloatStar	36.9	6.3	2.3	
Coarse cleaner 2	PID	41.1	9.8	2.8	**63.3**
	FloatStar	38.9	4.6	1.0	

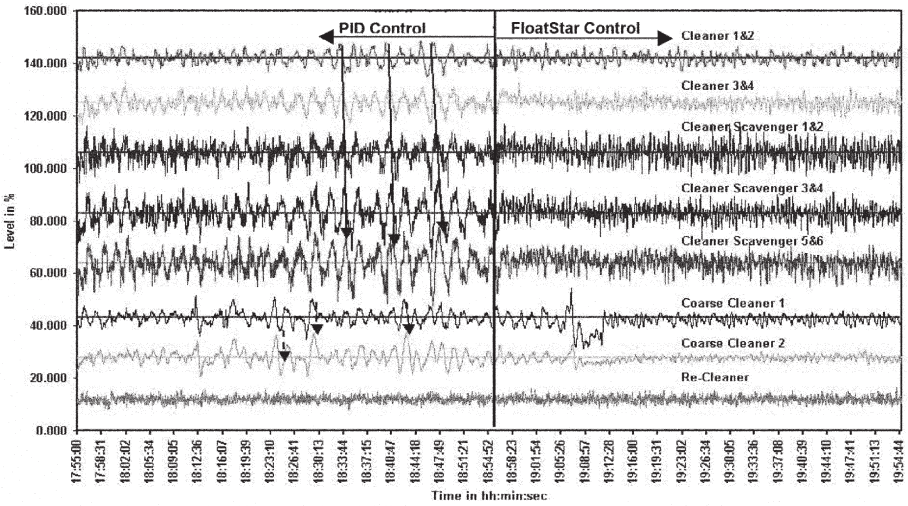

Figure 1—Comparison between conventional PID and FloatStar control for cleaner circuit

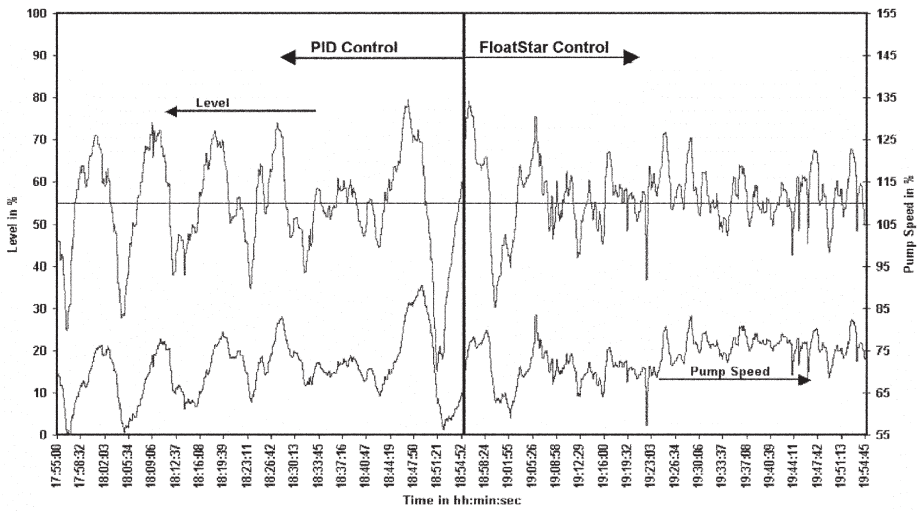

Figure 2—Comparison between conventional PID and FloatStar control for cleaner scavenger tails sump

Measured trends on cleaner circuit

A graphical comparison for conventional PID control versus FloatStar control is shown in Figure 1. The first hour shows the cleaner circuit under conventional PID control and thereafter under FloatStar control.

The configuration of the cleaner circuit is a re-cleaner, a five bank interconnected circuit from cleaner 1 and 2 through to cleaner scavenger 5 and 6, followed by a two bank interconnected circuit between coarse cleaner 1 and 2.

Figure 1 shows that the control on cleaner 1 and 2 under PID control is satisfactory. However, from about 18:19, minor oscillations begin and these oscillations propagate all the way through to cleaner scavenger 5 and 6. (See the solid arrows in Figure 1). The disturbance from coarse cleaner 1 passes through to coarse cleaner 2 as well. (See the dashed arrows.) PID control of the re-cleaner during this testing period is satisfactory; however, an improvement in control is achieved with FloatStar.

It is also evident from Figure 1 that the disturbance not only propagates downstream but also amplifies as it moves downstream. A closer inspection of cleaner scavenger tails sump level, shown by Figure 2, shows that the oscillations in cleaner 1 and 2 originate from cleaner scavenger tails sump. With FloatStar control the cleaner circuit stabilized and remained at setpoint for the rest of the testing period. Note that the propagation of disturbances from cleaner 1 and 2 to cleaner scavenger 5 and 6 has been eliminated with FloatStar control.

Measured trends of tails sump of cleaner scavenger

Figure 2 still indicates deviations in level from setpoint for the cleaner scavenger tails sump when in FloatStar control. The FloatStar control philosophy, however, takes the interacting effect of this sump on cleaner 1 and 2 into account and hence the reduction in deviation of level control in cleaner 1 and 2. Also, the plant performs conventional PID control while FloatStar used non-linear control for control of the sumps. The aim is to provide a constant flow rather than trying to achieve tight level control. A combination of non-

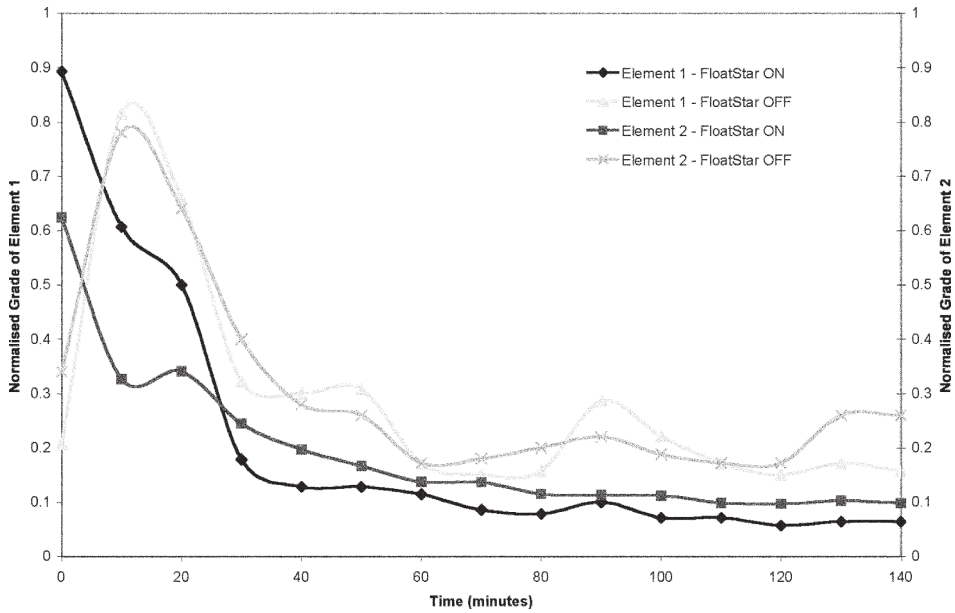

Figure 3—Comparison between PID and FloatStar start-up

linear (error squared) control and compensation for interaction though FloatStar control results in improved level control on the sump and the cleaner circuit.

With conventional PID control, the level of the cleaner scavenger tails sump is oscillatory and so is the control action (pump speed). As mentioned above, this passes a disturbance to cleaner 1 and 2 and to the rest of the cleaning circuit. With FloatStar control, the aim is not to have tight control on the level, but to provide a reasonably constant flow (pump speed) to cleaner 1 and 2. Figure 2 shows that this is being achieved.

Table II

Statistical summary of sumps level data

	Control	Mean Level	Level standard deviation	Error standard deviation	% Improvement
Cleaner scavenger	PID	55.0	11.6	7.9	**53.0**
	FloatStar	55.6	5.8	3.7	
Regrind sump	PID	54.9	11.7	8.8	**70.4**
	FloatStar	54.9	3.7	2.6	

Table III

Saving due to FloatStar during a start-up

Element 1 lost during start-up by PID control	Element 2 lost during start-up by PID control	Mass flow of tailing stream
0.1 normalized grade	0.15 normalized grade	*1469531 tons/mth 1975 tons/hr
Mass of element 1 lost 527 g 18.6 oz	**Mass of element 2 lost** 0.66 tons	**Time period of loss** 1.6 hr
Cost of element 1 lost USD 5183	**Cost of element 2 lost** USD 1006	
FloatStar savings on start-up USD 6189		*Obtained from plant

Start-up comparison

One of the main benefits of FloatStar is the faster stabilization time of the whole plant on start-up. An investigation of this point was planned and carried out by metallurgical staff. For the purposes of confidentiality, the two metals of interest will be denoted by element 1 and 2. After 2 maintenance shutdowns, during which the entire flotation plant was drained, samples of the final tailings stream were taken every 10 minutes following start-up and analysed for remaining element 1 and element 2. The results of the two start-ups are shown in Figure 3. It can be seen that the final tails grade drops to normal values after about 60 minutes when the FloatStar was controlling, while it never reached these values, even after 140 minutes when PID control was used. Quicker settling times mean that far less of element 1 and element 2 is lost to final tails during start-up or after plant disturbances. The results in Figure 3 indicate at minimum a 57% reduction in start-up times with FloatStar control.

Savings with FloatStar on start-up

Table III shows data for the calculation of the savings produced by FloatStar during a plant start-up. From Figure 3, FloatStar brings the plant to stable tailings grades after approximately 60 minutes. With conventional PID control, even after 140 minutes the tailings grade did not reach the stable tailings grades obtained by FloatStar.

From Figure 4 the amount of extra element 1 and element 2 lost to the tailings stream with conventional PID control is approximately 0.1 normalized grade and 0.15 normalized grade respectively for about 80 minutes.

Based on a mass tailings flow rate of 1 469 531 tons/month, this is equivalent to an additional 527 g of element 1 and 0.66 tons of element 2 that is lost to the tailings stream by conventional PID control during a start-up. In monetory terms this equates to USD 6189 (USD 5183 for element 1 and USD 1006 for element 2). This amount lost by the PID control will be gained with FloatStar.

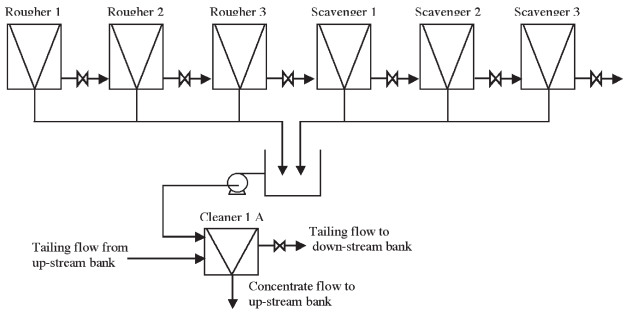

Figure 4—Rougher scavenger circuit

Flow optimizing control –industrial application

The FloatStar controller has a flow-optimizing module that was also installed on an industrial platinum flotation circuit. The results shown below achieve the following:

- rougher and scavenger level setpoint optimization
- cleaner optimization and mass flow control on final cleaning stage.

Rougher and scavenger level setpoint optimization

This part of the circuit consists of three roughers and three scavengers in series as shown by Figure 4.

The aim of the flow optimization is to control the flow into the cleaning circuit, which is actually the rougher, and scavengers concentrates. Since there is no measurement of flow into the cleaner, this flow was inferred by a special estimating filter based on available plant measurements. The filter used was a customized linear digital filter, the details of which are the subject of further research and are beyond the scope of this paper. It was a requirement of the plant to pull harder on the rougher and less on the scavengers. This was easily incorporated into the flow-optimizing controller by using the weighting option in the algorithm that allows the pull rates of the flotation banks to be varied as required by operators or metallurgists. With the inferred measurement of flow and a supplied setpoint for this flow, the flow optimizing algorithm was able to adjust the setpoints of the roughers and scavengers as shown by Figure 5.

As shown in Figure 5, the tailings flow (inferred from the estimating filter) from cleaner 1A was controlled to setpoint by adjusting the level setpoint of all the roughers and scavengers. It can also be observed from Figure 5 that the roughers have higher weighting for level setpoint changes compared to the scavengers. This was the requirement of the plant. The level setpoint changes are larger in magnitude for the roughers compared to the scavengers. Figure 5 also shows the steps that were made to cleaner 1A tailings flow setpoint and it is clear that the changes in level setpoints of the roughers and scavengers were adequate enough to track the new flow setpoints.

Cleaner optimization and mass flow control on final cleaning stage

Figure 6 shows the cleaner circuit where the flow optimization has been implemented. There are two stages of cleaning; essentially cleaner 1 and 2 are a single cleaning stage. The concentrate from cleaner 1 and 2 discharges into sump 1 that has a level indicator. The concentrate from sump 1 is then pumped to the final cleaning stage, cleaner 3, from where final concentrate is obtained.

The flow optimization was configured as follows:

The level of sump 2 was controlled to setpoint by changing the following two variables of cleaner 3:

- air valve position (therefore the aeration rate)
- level setpoint.

The mass flow rate (density multiplied with the volumetric flow rate) out of sump 2 was controlled to setpoint using the variable-speed pump.

The level of sump 1 was controlled to setpoint by changing the following two variables:

- level setpoint of cleaner 1
- level setpoint of cleaner 2.

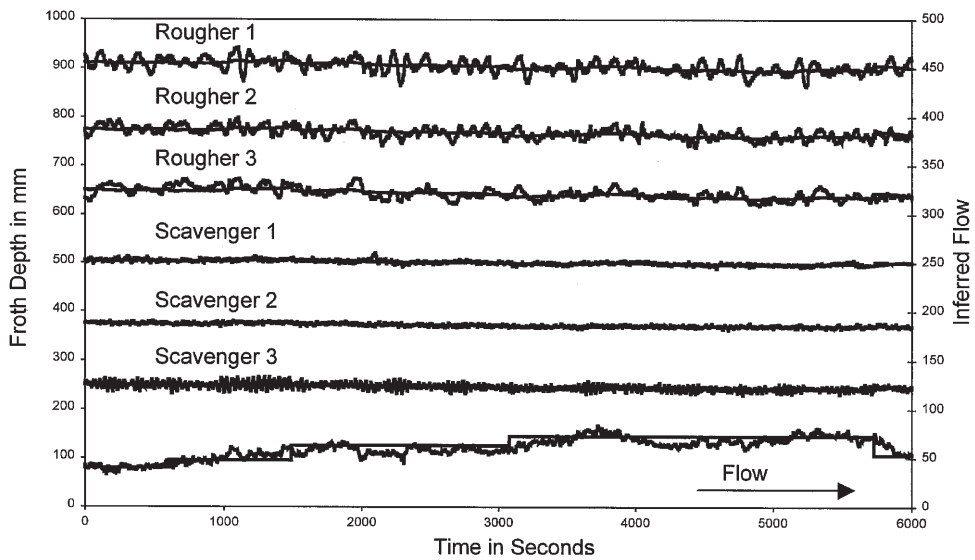

Figure 5—Rougher and scavenger level setpoint optimization

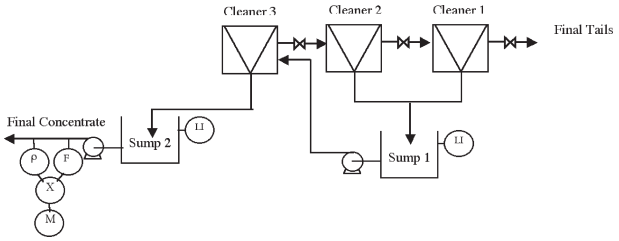

Figure 6—Cleaner circuit used for optimization

The following optional safety controllers were also implemented:

- If sump 2 level exceeded its maximum value, the setpoint for the mass flow rate was changed (within specified bounds) to keep the sump level at its maximum value. Once the level was controlled to within its limits, the mass flow rate setpoint was returned to the specified setpoint.
- If sump 2 level went below its minimum value, the setpoint for the mass flow rate was changed (within specified bounds) to keep the sump level at its minimum value. Once the level was back within its limits, the mass flow rate setpoint was returned to the specified setpoint.

Cleaner 1 and 2 level setpoint optimization

The level of sump 1 in Figure 6 was controlled by simultaneously manipulating the level setpoints for cleaner 1 and 2 using the flow optimizer. The results obtained are shown in Figure 7. The data in Figure 7 shows good setpoint tracking for the control of sump 1. This implies that the since the level in sump 1 is not changing much, the flow out of sump 1 will also be well controlled. During the installation it was found that cleaner 1 was slower to react to setpoint changes than cleaner 2. To counter this, the weighting on cleaner 2 was increased so that the level setpoint of cleaner 2 is moved more than that of cleaner 1. Hence cleaner 2 contributed more to the control of sump 1 than cleaner 1. The results for setpoint changes in the level of sump 1 are shown in Figure 7. As can be seen from Figure 7, the new setpoint for sump 1 is quickly reached.

Cleaner 3 level setpoint, aeration rate and mass flow optimization

Cleaner 3 is the final stage of cleaning and where the final product is obtained. (Refer to Figure 6.) It is very important for the plant that the mass flow from sump 2 is well controlled. Before controlling the mass flow from sump 1, the level of sump 2 needed to be controlled. Both the level setpoints and aeration rate of cleaner 3 could be manipulated and a change in concentrate flow in sump 2 will result. The flow optimization algorithm was configured on cleaner 3 to use both the air valve position and the level setpoint of cleaner 3 to control sump 2 level. During the installation it was observed that the response on sump 2 level when the air was changed was quicker and more pronounced than the level setpoint. Therefore the weighting on the air valve was made larger than that of the cleaner level setpoint. This resulted in sump 2 level being controlled mostly by the aeration rate into cleaner 3. Figure 8 shows the results that were obtained for sump 2 level control. As shown by Figure 8, the air valve moves more than the level setpoint. Good level control is achieved for sump 2.

The mass flow rate out of sump 2 was obtained by multiplying the volumetric flow rate with the density. This value of mass flow rate was incorporated into the flow optimizer to be controlled to setpoint by changing the pump speed. Figure 8 also shows that the results obtained for the mass flow controller is good.

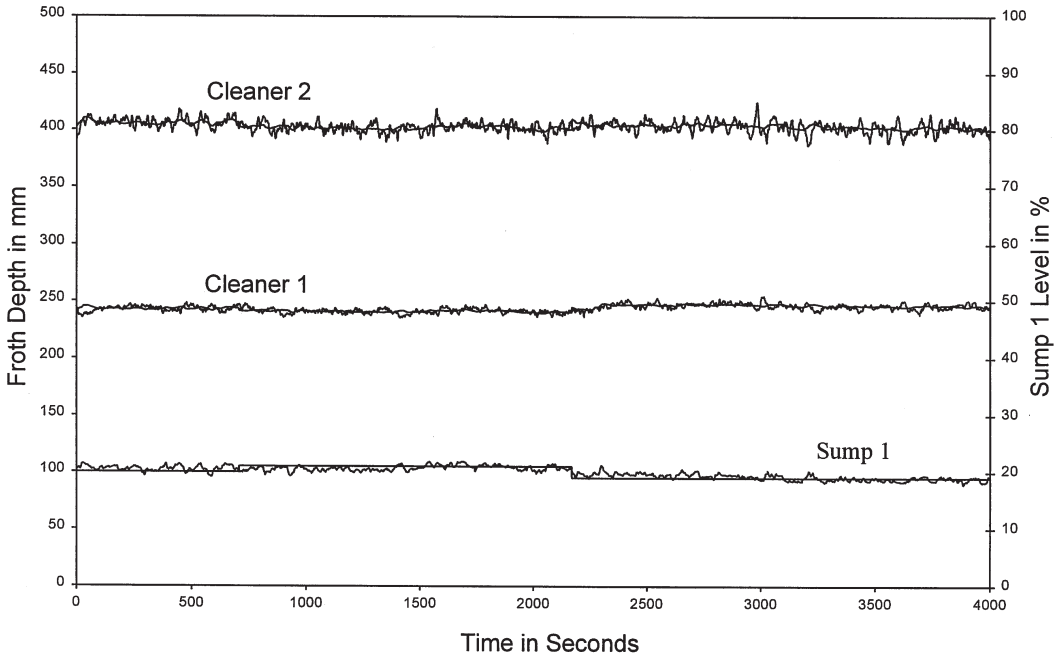

Figure 7—Cleaner 1 and 2 level setpoint optimization

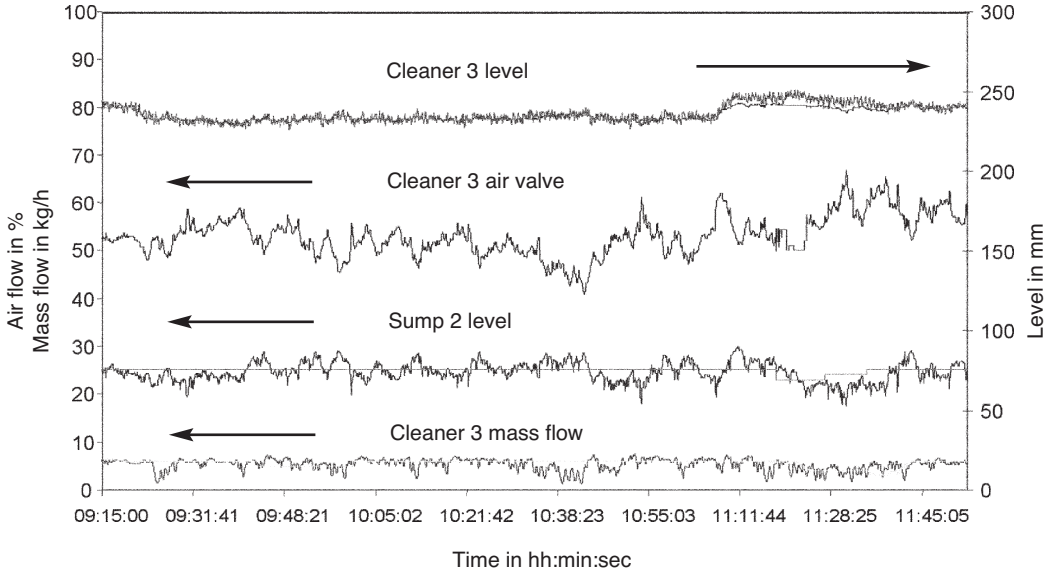

Figure 8—Cleaner 3 level setpoint, aeration rate and mass flow optimization

Conclusions

The FloatStar controller has been applied to a number of flotation circuits within and outside of South Africa. The controller is able to eliminate disturbances quickly and efficiently. FloatStar has excellent regulatory power and good servo control. One of the major advantages of the FloatStar is its ability to stabilize a plant during major plant disturbances or start-ups. On average it has been proven that the FloatStar provides a 1% improvement in recovery and reduces the start-up times of flotation circuits by approximately 67%. The good level control achieved by FloatStar provides a good basis for the optimization of flotation circuits.

The FloatStar flow-optimizing controller has given good industrial results. The controller is able to perform flow optimization by adjusting the level setpoint, aeration rate, or a combination of the two. Good concentrate mass flow and tailings flow control have been achieved with flow optimization. The flow optimization cascades new level setpoints to the level controller of FloatStar and in cases where the aeration rate can be varied, the flow optimizer will also adjust this variable to achieve a balance of flows. The controller is also able to bias the pulling rates of flotation cells by a weighting function in the flow optimizer. With the balancing of flows in a flotation circuit using the flow optimizer, the control of reagents will be able to fit in quite easily to achieve final concentrate grades and recoveries.

Acknowledgement

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